RESEARCH AND DEVELOPMENT OF COAL-FIRED FLUIDIZED-BED BOILER

Bao Dong-wen and Ruan Yi-shao

Research and Development Division
Dong-fang Boiler Works
Zigong, Shichuan, China

INTRODUCTION

The power industry in many countries is now facing a problem: how to achieve the inevitable shift from oil and natural gas to coal and low-grade coals while remaining in compliance with the regulatory limits on emissions. Fluidized-bed combustion (FBC) has demonstrated its potential to solve this problem, because it has the advantages of adaptability to low-grade coals and feasibility for sulfur emissions control. Due to FBC's relatively low combustion temperatures, NO_x emissions from a fluidized bed are lower than those from conventional furnaces.

As a new technology it is natural that there are many technical problems to be investigated and difficulties to be overcome in the development of fluidized-bed boilers (FBB).

Since 1971, Dong-fang Boiler Works (DBW) has carried out developmental work in FBB in the following areas:

- Combustion efficiency.
- Arrangement of fluidized-bed heating surfaces.
- Immersed superheater.
- Erosion of immersed tubes.
- Start-up of fluidized bed.

A 463 x 324 mm FBC test unit was built to investigate methods of improving the combustion efficiency of the FBB. Later, a 24 t/h stoker-fired boiler was converted into an FBB by DBW. It has now been successfully operated for more than 3 years, since 1977. The performance of the unit has been satisfactory to the user. Figure 1 shows the general arrangement of this modified boiler. Its major parameters are as follows:

Steam capacity	24 t/h
Steam pressure	32 kg/cm^2
Superheated steam temperature	450 ^{o}C
Feed water temperature	150 ^{o}C
Gas temperature at boiler exit	200 ^{o}C
Designed fuel	Bituminous coal

Natural circulation was adopted for the immersed evaporating surface. To date no problem in water circulation has occurred. An experimental immersed superheater was placed in the bed and its behavior observed. For distribution of combustion air, a refractory covered bubble cap plate was installed. In order to facilitate bed start-up and load changes, the windbox was divided into four separate compartments. Because bituminous coal was to be used, no carbon recycling was considered; thus the uncertainty of a recycle system was avoided. The once-through combustion efficiency (i.e., without reburning of elutriated fines) was measured as 94.8 to 95.5 percent.

TEST RESULTS AND DISCUSSION

A. Combustion Efficiency

When compared with pulverized coal firing, carbon losses from a fluidized bed are high as a result of the relatively coarse coal particulates and low combustion temperature. Combustion efficiency depends on the bed velocity and temperature, excess air, and on the coal characteristics (which have significant influence on carbon losses). Coal with high ash content and less volatile matter would have lower combustion efficiency. The following experimental data from the test rig demonstrate that c.e. values in burning different coals may differ greatly, even when the superficial velocity, bed temperature, and excess air rate are approximately the same.

	Volatile matters on combustible basis	Ash on analytical basis	Total carbon losses
Bituminous coal	35.48	31.40	3.77
Lean coal	17.50	39.04	10.67
Colliery wastage	48.09	76.50	7.95

If anthracite is burned, carbon losses will be higher than the above values. It is evident that application of FBC in utility boilers will require significantly increased combustion efficiencies.

Two approaches for improving combustion efficiencies are: using a carbon burnup bed (CBB) and fly ash reinjection into the main fluidized bed.

The effect of the CBB was examined using the 463 x 324 mm rig. The tests showed that with the use of a CBB (an efficiency of 80 percent was assumed for the cyclone dust collector), combustion efficiencies may reach values of 97.5-98.0 percent when bituminous or lean coals are burned.

The recycling or reinjecting of elutriated fines has not been tested, but judging from the literature of other countries and experiences in application of carbon recycling in some FBB in China, we can say that particulate recycling (especially for coals with high volatile matter content) is also an effective measure. For example, the combustion efficiency of a bituminous coal-fired combustor may attain ~ 98 percent.

When a CBB is used, in order to avoid high dust loading, the gas stream from the CBB must be directed to an individual gas flue. Therefore, the CBB is in essence a separate fluidized-bed boiler, which operates at different conditions from the main bed and needs its own particulate removal system. In addition to being a more complex system, the reliable combined operation of a CBB with the main fluidized bed is rather difficult because of the inevitable fluctuation of coal characteristics and the main bed exploitation; the recycle system is much simpler. The main disadvantage of recycling the dust recovered from the dust collector is the resulting high dust loading of the gas stream. The erosive characteristics of the dust must be determined by operating a demonstration unit over an extended period of time.

In our view, with regard to industrial FBB, the carbon recycling system may be more desirable in most cases. Where less reactive coal such as anthracite is burned and the high combustion efficiencies which are required for a utility boiler are pursued, the CBB system may have to be used.

The even distribution of coal over the bed has proved to be of significance for attaining good combustion efficiency. It has been reported that satisfactory coal distribution can be achieved if one feed point is provided for every 0.84 m of bed area. This would result in nearly 70 points for a 130 t/h unit. In order to meet the above requirement, a pneumatic method of transporting crushed coal may be necessary. However, for large FBB (e.g., 200 MW units) the feed lines and control system would become very complicated; therefore, a method to improve the area per feed point must be found if the pneumatic feed system is to be simplified.

For purposes of this test a pneumatic feed system was not considered, but four screw-type coal feeders were installed on the front wall. The area of distributing plate for the 24th FBB unit was 8 m^2; this provided one feed point for every 2 m bed area. To promote even coal distribution, a coal spreading method was developed. During the tests of this method on the 24 t/h FBB unit only two feeders were put into operation, which temporarily raised the area per feed point to 4 m^2. It was demonstrated that when the spreading device was used, combustion efficiencies were increased by 3.5-5.0 percent.

B. Arrangement of Bed Heating Surface

Vertical immersed tubes are generally used for small FBB. They are convenient for maintenance, and are more resistant to abrasion than horizontal tubes.

For larger units, to allow the necessary surface area required to be placed in the bed, horizontal or inclined buried tubes (staggered or in-line) are generally adopted. It is common knowledge that so far as convection surfaces are concerned, staggered tubes have higher heat transfer rates than tubes arrayed in-line. Given this information, is it still correct to use immersed tubes in FBB? To answer this question, special comparison tests were carried out. The results showed that, owing to the specific nature of the in-bed heat transfer, heat transfer coefficients for the in-line array of tubes fully compared with those for staggered tubes.

Initially, the immersed tubes of the 24 t/h unit were staggered. When the unit was put into operation, it was immediately discovered that excessive pulsations occurred and the erosion rates of the staggered inclined tubes and the fire brick walls were high.

On the basis of the above tests, it was decided to change the staggered tubes into in-line array. After the modification the steam output was maintained, the fluidizing quality became normal, and the abrasion rates were reduced.

C. Immersed Superheater

An industrial FBB can be designed with only an evaporating surface in the bed; this appears adequate to absorb the required amount of heat from the bed. In contrast, a certain portion of the superheating or reheating surface of a utility boiler must be placed in the bed in addition to the generating immersed surface. It seems useful to examine some problems of the buried superheater.

Because of the high heat transfer to immersed tubes (generally 220-250 kcal/m^2•h•^{0}C), it is of great importance to find out whether the wall temperatures of buried superheater tubes will exceed the limits. To this end, the character of the heat flux distribution along the periphery of an immersed tube must be determined. Special tests showed that this distribution was uneven, and surprisingly, the highest heat flux point was found at the upper part of a horizontal buried tube (Figure 2). The maximum heat flux exceeded the average value by 15-30 percent (in some cases even more), which means there exists an intense circulating flow of particulates within the "cap area" above the immersed tube. Figure 3 illustrates the approximate manner of particulate circulation.

ϕ42 x 5.5, 12 Cr/MoV steel tubes were used for the experimental submerged superheater. The steam velocity was ~ 35 m/s and the mean exit steam temperature ~ 420^{o}C. Thermocouples were placed on the outer surface of the lower part of two buried superheater tubes. No thermocouple was placed on the upper part of the tubes, because it was thought that the maximum heat flux area must be at the lower half periphery; thus, the maximum tube wall temperature was not measured. The temperatures taken from the lower half periphery were 530^{o}-550^{o}C. It was clear that the wall temperature at the top of the tubes must have been higher. After about 3 months of operation, a metallographic examination was made of the tube. It was found that grade 3 spheriodization had taken place at the top of the tube, which meant that although the steam temperature was as low as 420^{o}C, using the 12Cr/MoV steel tube was not safe. It appears that the tube wall temperature must be considered carefully and high-quality heat resistant alloy steel will have to be used when superheating or reheating surfaces need to be placed in the bed.

The protection of the immersed superheater during start-up and bed slumping was also of considerable concern. As operating experience had proved, the buried superheating tube temperature would not exceed the allowed value during start-up and slumping, provided the surface was arranged properly and partial bed start-up sequence (a portion of the bed where the immersed superheater is located, lit up only after an adequate steam flow is established) was adopted. When the boiler was to be shut down and the bed slumped, the immersed superheater would be safe. The immersed superheater was arranged above the slumped bed and its wall temperatures, measured during slumping, were all lower than 530^{o}C. The temperatures measured in the space between the superheater and slumped bed did not exceed 600^{o}C.

The temperature distribution over the bed was relatively even, and the deviation in heat absorption among the individual tubes was not great. Generally speaking, the deviation coefficient is about 1.1, provided the surface is appropriately designed. The temperature gradient along the feeder axis may be somewhat greater; therefore, the tubes of an immersed superheater would preferably be oriented in parallel with the feeder axis (as shown in Figure 1). If bed temperature unevenness along the feeder axis is significant and the superheater tubes are at right angles to the feeder axis, higher deviation coefficients of 1.20-1.26 may be reached, depending on the bed temperature gradient.

D. Erosion of Immersed Tubes

At present, rather coarse coal particulates are generally used in China. Consequently, high fluidizing velocity has been adopted. Many years of operational practice has shown that in most cases the abrasion of inclined buried tubes is very severe. For example, tubes (20 carbon steel) with a thickness of 3 mm may wear out after only ~ 4000 hours of operation. The most serious abrasion usually occurs in the first (lower) row of inclined buried tube surfaces. Along the inclined tubes certain more severely abraded sections can be observed. The abrasion rate is very uneven along the tube periphery. Figure 4 illustrates the severe abrasion of a 20-carbon steel tube with a thickness of 6.25 mm (no antiabrasive treatment used) after 8682 hours of operation. The abrasion rate at the bottom of the tube is three times as high as that at the top. Several types of antiabrasive treatments for immersed tubes were tried, and some of them have showed effect. However, when relatively hard coals are burned these measures can only extend tube life to a certain degree, therefore the abrasion problem cannot be regarded as solved. Lignite-fired, fluidized-bed boilers may be the only exception. The erosion rate of their immersed tubes is not high, owing to the softness and light weight of the lignite.

It seems to us that low fluidizing velocity should be accepted as the primary measure for extending the life of immersed tubes, with additional antiabrasive treatment when necessary. This may be the final solution to the erosion problem. Besides the diminished tube abrasion, low fluidizing velocity may offer other benefits such as higher combustion efficiency, better SO_2 absorption (when limestone or dolomite is added to beds where high-sulfur coal is burned), and the possibility of using shallow beds to reduce the amount of blower power required. In order to lessen the abrasion rate, the immersed tubes should be reasonably arranged to avoid excessive pulsations and gas flow imbalances in the bed.

E. Start-up of Fluidized Bed

The process of start-up is, in essence, to heat the bed material to a temperature high enough for stable combustion of coal. It seems very simple, but when boiler service is initiated operators often run into trouble.

"Fixed state" start-up is a method adopted in the initial period of FBB development in China. In this process, the bed remains fixed at the beginning of start-up. When the bed material has been heated to the appropriate degree, the bed is tranformed from a fixed to a fluidized state and continues to be heated to the required temperature. During the start-up process, clinkering or flame failure may easily take place if the heat balance is not properly controlled. Exploitation depends to a great extent on the operator's experience, so it is not completely reliable. Furthermore, the time required for starting up is rather long.

Through the search for a better method, the so called "fluidized state" start-up technology has been developed. The major feature of this process is that the bed is brought to fluidization at the very beginning of start-up. The fluidized bed is heated up by an oil burner; the heating is uniform and steady. In 10-20 minutes, a bed with an area of 4 m^2 can be heated from ambient temperature to 900°-1000°C. It is much quicker than the "fixed state" method, and oil consumption can thus be reduced. Figure 5 shows a typical bed start-up curve in which the "fluidized state" method was used.

CONCLUSION

The main reason for developing fluidized-bed boilers in China is to burn high-ash coal of low calorific value, and thus broaden the scope of energy resources. This appears to be especially important in the southern provinces. Practice over a number of years has indicated that FBB are promising, at least for industrial boilers and small electricity generating units in China. The application of FBB to utility power plants, however, depends on future development, economic factors, and the success of intermediate demonstration units.

There is no doubt that many areas still need further investigation and that equipment could be improved, but we are convinced that a good start has already been made. Dong-fang Boiler Works now produces commercial FBB with steam capacity of up to 35 t/h. Units of greater capacity are under consideration.

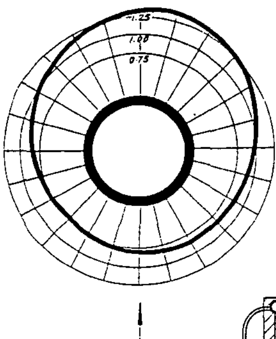

Fig. 2 - Heat Flux Distribution

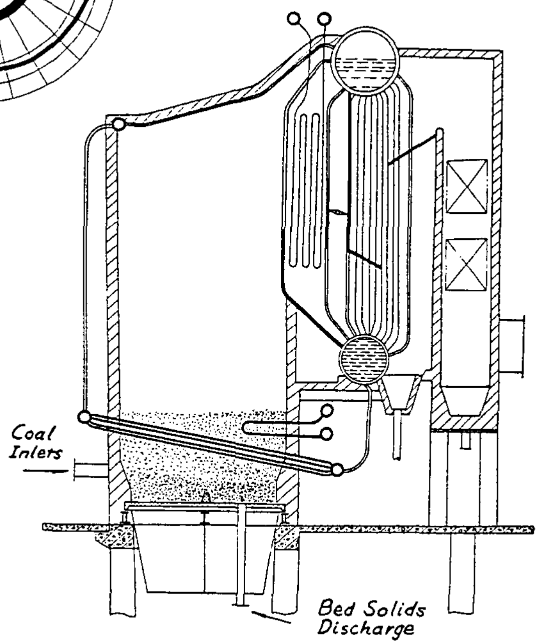

Fig. 1 - 24 t/h Fluidized Bed Boiler (modified)

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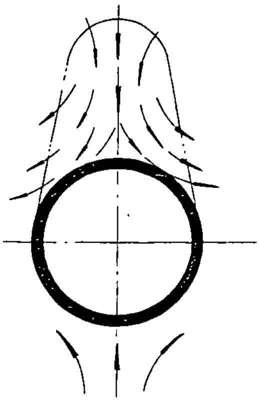

Fig. 3 - Particulate Circulation in "Cap Area"

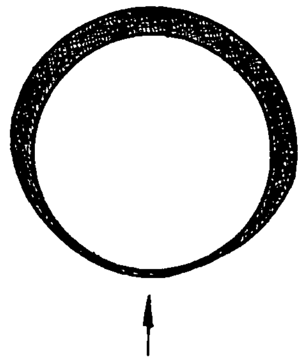

Fig. 4 - Wornout Tube

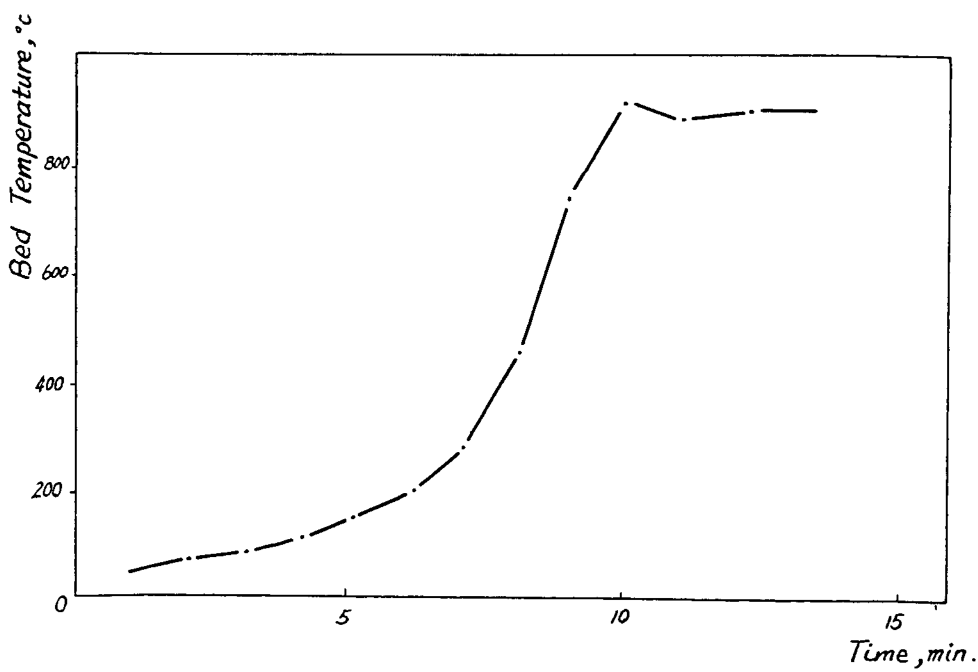

Fig. 5 - Bed Start-up Curve